HIGH-VOLTAGE SPIRAL GENERATORS*

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ABSTRACT

The performance of Spiral Generators operating at high output voltage is described. Generators employing castor oil impregnation are compared to those with air insulation. Tests on oil-insulated generators with output capacitance of about 1 nF indicate their high voltage capability is up to 1 MV. Generator failure at high output voltage appears to be caused, in part, by the initial dc charge voltage, thereby limiting the allowable stored energy. Recent preliminary data suggests this limiation may be overcome by including resistive paper in the generator winding. Also discussed are switching techniques applicable to Spiral Generators or other sources requiring a low-inductance input switch. Solid-dielectric multichannel switches are found particularly suitable for Spiral Generators.

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Introduction

Recent development work on spiral-line generators has resulted in a compact, high-voltage capacitive source for applications where low cost and portability are prime factors. A spiral-line generator[1] is composed of a strip transmission-line wound into a spiral thereby forming a hollow cylinder. The two electrodes are insulated from one another with solid-dielectric film; an additional film of dielectric is included on the outside of the strip-line to provide turn-to-turn insulation as shown in Figure 1. The solid insulation is wider than the conductor width to provide a margin which inhibits edge-to-edge breakdown of the conductors. In addition to this margin, the edges may be further insulated with liquid or gas of high dielectric strength.

During operation, the strip-line is dc charged between 10 kV and 50 kV. Then the input switch S_1 is triggered which inverts the electric field between the strip-line conductors; the electric field in the insulation between turns is unaffected by the switch closure. The field inversion causes the electric field lines to align radially thereby creating high-voltage between the inner and the

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outer turn. The end of the strip-line opposite the input switch rises in voltage with a ramp-like waveform until peak occurs after two electrical transit-time along the length of the spiral. Assuming no losses, this peak is $2nV_i$, where n is the number of turns and V_i is the initial charge voltage. Losses reduce this voltage to a fraction β of the ideal amplitude. In practice β has been between 0.3 and 0.5 for generators studied during this program.

The output capacitance of the generator is derived by setting the initial stored energy equal to the output energy, as follows:

$$1/2\, C_i V_i^2 = 1/2 C_o V_o^2 \; .$$

Substituting $2nV_i$ for V_o results in the following equation for effective source capacitance:

$$C_o = \frac{1}{(2n)^2} C_i$$

This report describes tests on two generator designs: a 1 nF source about 1-1/2 ft. in diameter by 3 ft. in length and weighing about 150 lbs, and a 0.1 nF source about 10 in. in diameter, 1 ft. long weighing about 30 lbs.

Comparison of High Voltage Generators

Spiral generators can be viewed as an attractive alternative to transformers for providing voltage gain. For example, a Martin autotransformer is basically a spiral of copper foil with mylar insulation between the turns, and aqueous $CuSO_4$ impregnated into the windings to grade the foil edges. To attain voltage gain from a transformer, external dc energy storage, as in a capacitor or capacitor bank, is required to discharge into the primary. On the other hand, the spiral generator utilizes a pair of conductors for both dc energy storage and for creating high-voltage. That is one of the main reasons the spiral generator has potential as a high energy per-unit-volume and per-unit-weight source. However, use of the windings for initial dc charge prevents the use of aqueous $CuSO_4$ as an edge grading medium; therefore, an alternative such as resistive paper or plastic is required. Aqueous $CuSO_4$ is an excellent grading material because of its easily controlled resistivity and its availability, in contrast to paper or plastic films.

Compared to Marx generators, spiral generators share a common advantage with transformers: a single input-switch is required to initiate the high-voltage output waveform. In contrast, Marxes require multiple switches which tend to increase relative size, weight and complexity. However, the edge-insulation problem tends to be more severe when the full generator voltage appears across a single winding, as in spiral generators and transformers, compared to a fraction of full voltage across each of a number of smaller windings as in Marx generators. Therefore, for spiral generators to be used to full advantage, careful insulation of the foil edges is essential.

Air-Insulated Spiral Generators

Early spiral generator tests at MLI utilized ambient air as an edge grading medium. These generators had about 1 nF output capacitance and about 40 turns. Figure 2 shows a typical 1 nF generator equipped with a multichannel gas input-switch for operation between 15 kV and 30 kV dc charge. Also shown is a 1 MV gas output-switch positioned along the generator axis. The output switch insulates the load from the generator during the slow rising erection waveform. When the desired voltage is reached the output switch self-closes providing a fast rising waveform to the output load. The load impedance is connected between the spherical corona shield and the outermost turn of the generator. When output voltage in the 600 kV range was attained, surface tracking occurred which short-circuited the generator output. In general, these tracks extended from the inner to the outer foil edges but did only superficial damage to the mylar insulation. The generator was capable of repeated operation at or near the voltage at which tracking occurred.

In these air-insulated generators the initial dc charge voltage was also limited by surface tracking. A margin size of about 6 inches was required to hold $\sim$ 25 kV dc, thereby limiting the initial energy storage in a generator with given margin size. In light of the experience in air, alternative edge insulations were sought to increase both the initial charge energy density and to permit higher output voltage without surface tracking problems.

Foil-Edge Breakdown

Scaled breakdown experiments were performed which simulated the edge field which occurs in spiral generators. Disk samples, as shown in Figure 3, were tested in air, SF_6, and castor oil using realistic waveshapes with peak voltage to about 250 kV. As shown in the data summary of Figure 4, the castor oil immersed samples had the highest breakdown strength which motivated the use of castor oil as a generator impregnant.

Oil-Insulated Spiral Generators

Generators were tested with 1-1/2 ft. diameter and 3 ft. overall length (2 ft. foil width). They were wound from two 10 mil conductors, insulated with 10 mil mylar, and vacuum impregnated with castor oil at a temperature of about 150°F. The test setup is shown in Figure 5 and a typical output voltage in Figure 6. They were capable of repeated operation at about 700 kV. When they were charged to higher voltage, 1 MV peak voltage was attained. Due to the 1 MV shot, however, edge fialure occurred preventing subsequent charge.

Experiments were also conducted with 1 ft., 30 lb. generators to assess methods of reducing generator weight. The main contributor to weight is the foil. Generators with reduced foil thickness were tested for their maximum dc charge and output voltages. Forty-turn generators were wound which were 8 in. diameter and one foot long with output capacitance of about 100 pF. The tests showed 5 mil foil thickness reduced the allowable dc charge voltage from about 30 kV to 25 kV and correspondingly reduced peak output voltage, even when special care was taken with the foil edge. If this maximum were exceeded the insulation at the foil edge would fail during the time the generator was being dc charged.

Conventional edges are burred during manufacture. On special order, foil with full-radius edge and with precision cut burr-free edge was obtained. Experiments showed the edge quality had no significant effect on peak dc charge voltage or peak output voltage.

DC Charging Effects

Generators with 2 ft. foil width were compared to those with 6 in. foil width when foil and film thickness (10 mil each) were held constant. In each case, a maximum dc charge voltage of about 30 kV was obtainable. Above that value, insulation failure at the foil edge occurred prior to triggering the input-switch. Maximum output voltage was different in two cases: the generators with foil width of 2 ft. erected to 1 MV, those with 6 in. foil width, erected to $\sim$ 600 kV, yet both suffered edge failure. This suggests the edge destruction was caused by the dc charge of the generator and that reduction of the field at the foil edge can increase operating voltage. Search for an edge-grading material resulted in a resistive paper of 10 MΩ/square resistivity. The paper was wound into the generator so that each foil was sandwiched between two sheets of paper.

Preliminary experiments on three generators with 6 in. foil width, 5 mil thickness, and 10 mil mylar thickness indicate they now can accept a 50 kV dc charge (compare to 25 kV without resistive paper) and erect to 1 MV. The 5 kV/mil dc stress is probably approaching the maximum mylar can sustain without breakdown. The MV output caused these generators to undergo edge failure which indicates the paper resistivity was too high to grade the foil edge for operation in the megavolt range. The choice of 10 MΩ/square resistivity was made on the basis of availability although calculations indicated lower values would provide better field relief without introducing noticeable resistive loss; optimizing this resistivity can result in significant improvement in generator performance.

Input-Switch

To maximize output voltage from a given generator, the input switch rise-time L/Z must be about one-tenth the double transit-time of the spiral. For example, a typical spiral length was 125 ft. (400 ns double transit-time) and the input impedance of a 2 ft. wide line insulated with 0.010 in. mylar is 0.1 Ω. The switch inductance should be less than 5 nH. To attain this low inductance, gas or solid-dielectric multichannel switches can be used. Much of the present work employed solid-dielectric switches because they can operate at any desired input voltage of interest between 5 kV and 50 kV or higher, simply by varying mylar thickness. This range cannot be obtained with a single rail gap. With solid switches, setup shots were fired at low voltage without risk of generator damage. Figure 7 shows a diagram of the solid-dielectric switch.

Summary

The high-voltage capability of spiral-line generators has been increased to the point where generators may be operated up to a megavolt with delivered energy in the kilojoule range. These high-voltage generators require castor oil impregnation and resistive paper to provide edge-grading. The development work included solid-dielectric switching enabling the required performance to be obtained in a compact and lightweight system.

Acknowledgements

The authors would like to acknowledge the contributions to this program made by the originator of Spiral Generators, Mr. Richard Fitch of Maxwell Laboratories.

Reference

[1] Fitch, R. A. and Howell, R. T. S.; "Novel Principle of a Transient-High-Voltage Generator", Proc. IEE, Vol. III, No. 4, April 1964.

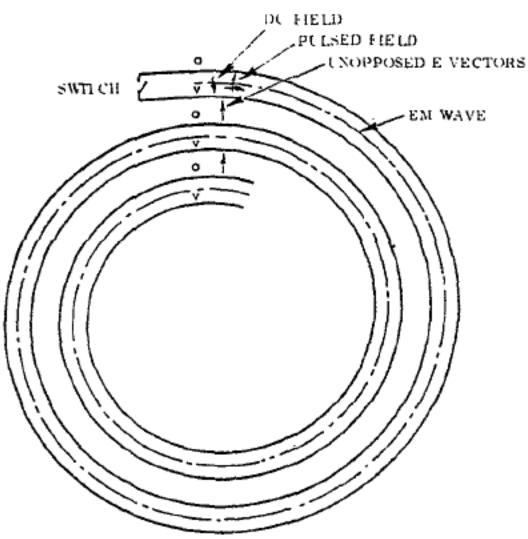

Figure 1. State of Spiral Generator at $t = 1/2\tau$.

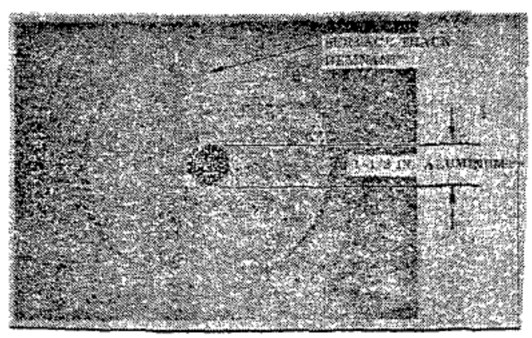

Figure 3. Photograph of Typical Foil/ Mylar Laminate with Surface Track.

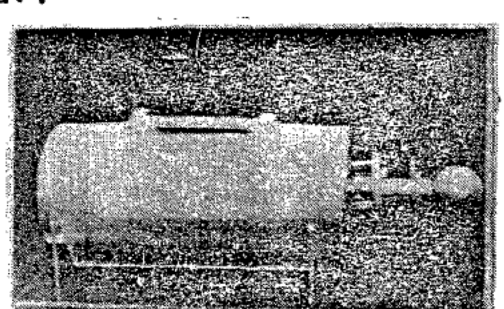

Figure 2. Photograph of Spiral Generator Prior to Impregnation with Castor Oil. The Input Gas-Dielectric, Rail Switch is 1 ft Long.

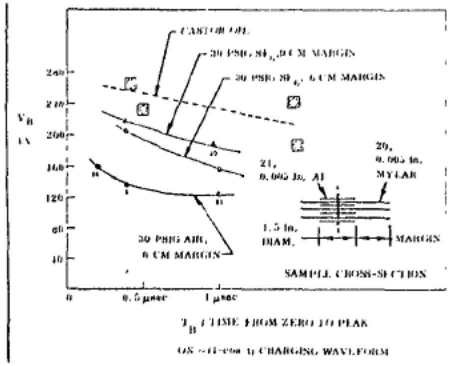

Figure 4. Breakdown Voltage Versus Time for Gas and Oil Insulated Samples.

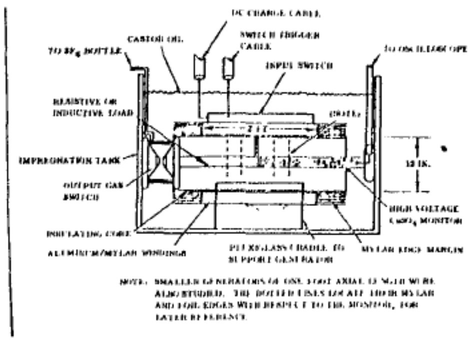

Figure 5. Spiral Generator in Impregnation Tank, Ready for High Voltage Test.

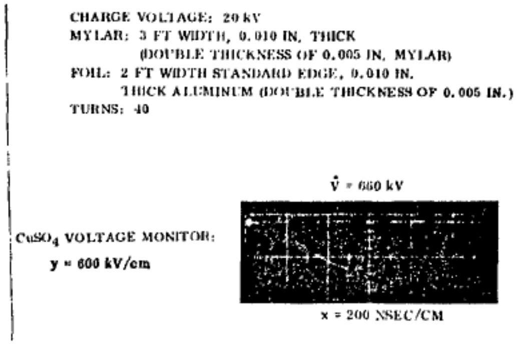

Figure 6. Output Voltage from Spiral Generators, with 3 ft. Axial Length.

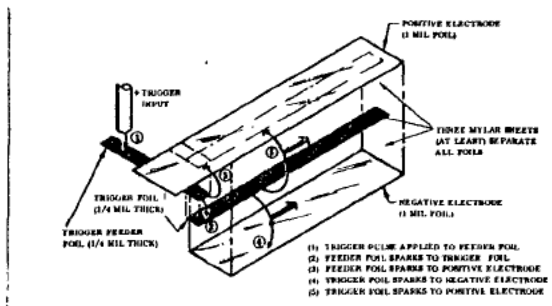

Figure 7. Solid-Dielectric Triggered Switch.